

Proxies of the East Antarctic shield: Composition and age of ice-covered basement from sedimentary and glacial provenance

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Summary The Precambrian East Antarctic shield is the last geological frontier on the planet. Because of its thick ice-sheet cover, very limited exposure, continental scale and extreme challenge in obtaining sub-ice samples, little is known about the composition and structure of its interior. A potentially rich body of information can be obtained, however, from sedimentary and glacial deposits found along the shield margin. Here I discuss several approaches to using such sedimentary and glacial proxies from two sections of the East Antarctic shield adjacent to the central Transantarctic Mountains and the Wilkes Land margin near Terre Adélie. In each area, transported rock clasts and sediment can be used for petrographic study, geochemical analysis, clast geochronology and detrital-zircon geochronology. Together, integration of data from petrologically-distinctive individual clasts and large detrital zircon populations provides a good first-order representation of the hidden East Antarctic shield terrains underlying different sections of the ice sheet.

Citation: Goodge, J. W. (2007), Proxies of the East Antarctic shield: Composition and age of ice-covered basement from sedimentary and glacial provenance, in *Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES X*, edited by A.K. Cooper and C.R. Raymond et al., USGS Open-File Report 2007-1047, Extended Abstract 132, 4 p.

Introduction

The East Antarctic shield (EAS) represents one of Earth's oldest and largest cratonic assemblies, with a long-lived Archean and Proterozoic history. It is the central piece in the eastern Gondwanaland mosaic, and it likely played an important role in the Neoproterozoic amalgamation of the Rodinia supercontinent. The thickness and geothermal properties of this shield governed initiation of the overlying East Antarctic ice sheet and today affects its stability. A clear understanding of the geological evolution of the EAS therefore provides an essential foundation for studying early crustal evolution, as well as subsequent resource distribution, biosphere evolution, and glacial and climate history. The history of the EAS, known from fragmentary evidence along coastal outcrops (Fig. 1), is thought to be episodic and composite in nature. Because of nearly complete coverage by the polar ice cap, however, the EAS remains the most inaccessible and unexplored geological feature of the Earth.

A variety of methods can be used to remotely examine the ice-covered Precambrian shield of East Antarctica, including over-ice potential-field geophysics and sub-ice drilling. Because these approaches are costly and logistically difficult, however, sedimentary and glacially-transported materials can be used effectively to characterize the composition and age of ice-covered basement. In the examples provided here, Neoproterozoic to lower Paleozoic marginal-basin sediments, Permo-Jurassic terrestrial sediments, Neogene to Holocene glaciomarine deposits, and Pliocene to Late Pleistocene diamicts and tills provide valuable proxy samples of the shield interior.

Central Transantarctic Mountains

The central Transantarctic Mountains (TAM) is the only section of the Ross Orogen where crystalline basement rocks of the EAS are exposed. High-grade, penetratively-deformed metamorphic and igneous rocks of the Nimrod Group, well exposed in the Miller and Geologists ranges, provide ample isotopic and geochronologic evidence of their Archean and Paleoproterozoic ancestry. Structural, petrological and thermochronological studies have resolved geological events at ca. 3.0, 2.5, 1.7 and 0.5 Ga, the latter corresponding to the Ross Orogeny involving peak metamorphism, deformation, syn-tectonic igneous activity, and cooling between about 540-485 Ma. Outboard of the Nimrod basement lie low-grade siliciclastic and calcareous rocks of the Beardmore and Byrd groups. The lower sedimentary succession includes upper Neoproterozoic to Lower Cambrian rift- to passive-margin deposits (Beardmore and lower Byrd Groups, respectively), overlain by widespread molasse deposits that record deep erosion of the Ross Orogen and exhumation of the igneous and metamorphic basement (upper Byrd Group; Goodge and others, 2004). As elsewhere, igneous rocks of the Granite Harbour series intruded the supracrustal assemblages between ca. 540-480 Ma. Proxy basement information can be obtained from provenance studies of the Neoproterozoic-lower Paleozoic rift-margin deposits and Pliocene to recent ice-contact deposits that occur along the plateau side of the TAM divide.

Neoproterozoic and lower Paleozoic rift-margin sediments

Upper Neoproterozoic and lower Paleozoic siliciclastic rocks in the central TAM were deposited in a rift-margin to passive-margin setting along the paleo-Pacific margin of East Antarctica. U-Pb detrital zircon ages used to constrain their depositional age and sedimentary provenance also provide information about the adjacent East Antarctic basement. The oldest passive-margin deposits (Beardmore Group) contain a variety of Archean and Proterozoic age components, reflecting distal input from the adjacent cratonic shield, Mesoproterozoic igneous provinces, and Grenville-age parts of

East Gondwana. Source terrains of similar age are widespread in East Antarctica and adjacent areas, including the nearby Nimrod Group, accounting for common age components of ca. 3.0, 2.5 and 1.7 Ga. Neoproterozoic belts of Grenville-type affinity occur in a number of areas, and several distinctive sub-belts are recognized at ca. 1175, 1080, and 960 Ma in the EAS. The TAM sandstones appear to contain only the older of these Grenville-age subcomponents (1235-1095 Ma), suggesting that the principal source of passive-margin detritus was in the Wilkes Land sector of East Antarctica and adjacent western Australia. Likewise, basal sandstones of the Lower Cambrian Shackleton Limestone (lower Byrd Group) and the latest Neoproterozoic Koettlitz Group in southern Victoria Land contain zircons reflecting a cratonic shield source, but these platform sediments also contain younger detrital components between 1000-970 Ma in addition to the older Grenville ages, which may indicate a broader source region that included basement in southern India and adjacent Rayner Complex of East Antarctica.

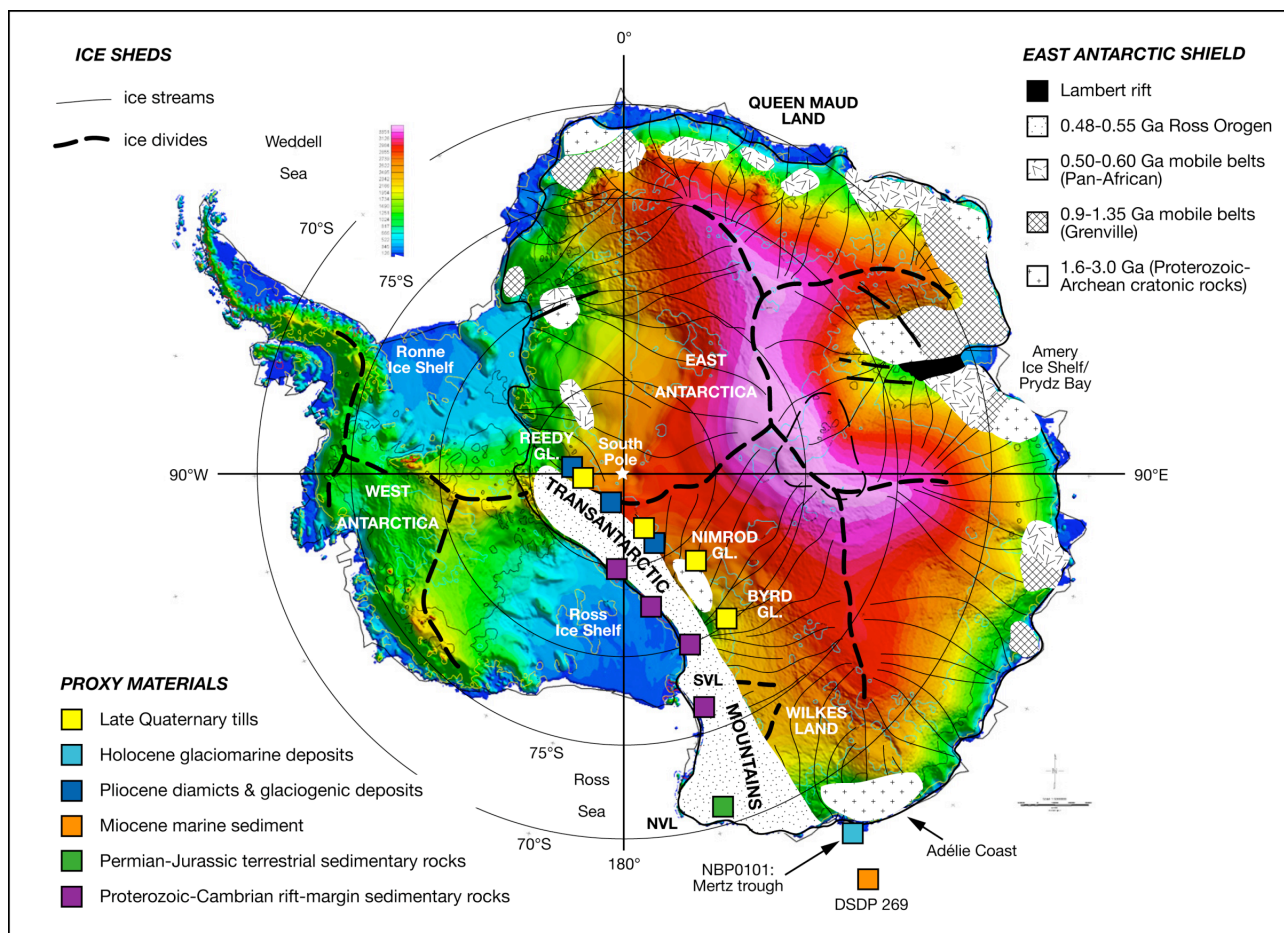


Figure 1. Map of Antarctica showing elevations of East and West Antarctic ice caps (Lythe et al., 2001), principal East Antarctic shield geology (after Fitzsimons, 2000), modern glacial flow (after Barker et al., 1998), and study areas used for sampling of sedimentary and glacially-transported proxies. Warmer colors indicate higher ice-surface elevations.

Detrital age data from autochthonous passive-margin and platform units in the central TAM also support a paleogeographic link to western Laurentia. These deposits contain significant proportions of ~1.4 Ga zircon (up to 22%). Geologic provinces of ~1.4 Ga age are uncommon globally, and the most significant potential source of sediment of this age is the widespread trans-Laurentian A-type igneous province (Goodge & Vervoort, 2006). Detritus of this age cannot have originated in Laurentia directly, as paleogeographic models indicate East Antarctica and Laurentia were separated prior to Early Cambrian time. Therefore, the persistent signature of ~1.4 Ga material in sandstones from the central TAM suggests that the primary source of this material in the rift-margin successions is a Proterozoic geologic province within the central EAS containing rocks of 1.4 Ga age. Such a crustal province may be an extension of Proterozoic belts in Laurentia, including the 1.4 Ga igneous rocks and their hosts in the Yavapai, Mazatzal and Mojave provinces. This interpretation is consistent with the co-occurrence of 1.8-1.6 Ga zircons in the detrital populations. Further support for this provenance linkage between East Antarctica and Laurentia comes from Hf-isotope compositions of the ~1.4 Ga detrital zircons, which closely match distinctive isotopic compositions in the Laurentian granites.

Neogene Sirius Group

Sub-glacial diamictites and glaciofluvial to glaciolacustrine deposits of the Sirius Group occur in southern Victoria Land and the central TAM. Although there is controversy about how far the sediments have been transported, most ice flow directions indicate a likely source in the East Antarctic interior. The Sirius includes a variety of ice-contact and subaqueous deposits, including lodgement till, glaciogenic debris flows, glaciofluvial sediment, and laminated glaciolacustrine deposits containing ice-rafted clasts. These deposits occur on the plateau side of the mountain belt, so they offer an opportunity to sample detritus of the shield interior. Sand-size fractions from samples of tillites, diamicts and laminates are currently being analyzed for detrital zircon age distribution in order to determine source patterns in the Beardmore, Shackleton and Reedy glaciers areas.

Late Quaternary tills

Glacial till deposits on the ice cap side of the TAM contain materials eroded from beneath the EAIS and thus represent a sampling of the sub-ice geological provinces comprising the EAS. Since it is logistically difficult to sample sub-glacial till beneath the outlet glaciers or immediately in front of them, recent tills deposited along the polar plateau side of the TAM provide an easily-accessible, naturally-concentrated sample of the rock types eroded by the EAIS. Additionally, the subglacial tills are essential for interpreting the provenance of Late Quaternary Ross Sea deposits for paleo-ice flow reconstructions (Licht et al., 2005). Late Quaternary till samples collected from exposures along the polar plateau side of the TAM in the Byrd, Nimrod, Beardmore, Shackleton and Reedy glaciers areas are currently being analyzed for their particle size distribution, clast lithology, whole-rock clast geochemistry, sand petrography, Nd, Sr and Pb isotopic composition and elemental abundance of the silt/clay fraction, and U-Pb ages of detrital zircons.

Wilkes Land margin

The Wilkes Land continental margin, formed during Gondwana breakup and separation from southern Australia, is underlain by Early Cretaceous sedimentary basement and an unconformably overlying Cretaceous to Miocene fluvial-marine succession; the latter includes continental-rise turbidites with glacial sources. This succession is overlain by subglacial and glacial-marine deposits resting on a Late Eocene or Early Oligocene unconformity surface that marks the onset of glaciation on the East Antarctic shelf. The present-day shelf morphology shows high-standing flat-topped banks and deep linear troughs, the latter interpreted as scour features formed by ice streams during the Last Glacial Maximum (LGM) advance. The Wilkes Land margin is capped by Holocene glacial-marine deposits, including massive to stratified diamictites and overlying diatomaceous mud and ooze. Sedimentary lithofacies and provenance data indicate that the Holocene glacial deposits have a continental basement provenance. Samples of Holocene glaciogenic shelf deposits (sandy intervals from piston cores and lithic clasts from dredge hauls), Miocene marine sandstones deposited after the onset of glaciation, and Permian-Jurassic terrestrial sandstones have been studied in order to trace inputs from the adjacent Wilkes Land shield basement.

Permian and Jurassic terrestrial sediment

Terrestrial strata of the Beacon Supergroup occur in the Rennick Glacier area of northern Victoria Land. These units rest on lower Paleozoic crystalline basement and consist of terrigenous fluvial sandstone with minor calcareous and non-calcareous mudstone deposited in sandy, braided stream systems with a source in Victoria Land and/or the central Ross Orogen. Detrital zircon ages were determined for samples of the Permian Takrouna Formation and Jurassic (new age) Section Peak Formation. Both units are dominated by Pan-African- and Grenville-age components, a common feature for sediments deposited along the Pacific margin of Gondwana. Neither of the Beacon sandstones contain significant Precambrian detritus, consistent with the interpretation that Beacon deposition was chiefly a result of erosion from Pan-African-age orogenic systems in present-day Africa and East Antarctica. Although basal sections near the basement unconformity appear more likely to provide information about the underlying Precambrian basement, detrital zircon ages from these terrestrial sediments indicate that the younger glaciogenic deposits from the Wilkes Land margin do not contain significant second-cycle material from older cratonic basins.

Miocene marine sediment

The Wilkes Land continental slope and adjacent South Indian Abyssal Plain contain mostly Neogene marine silt and clay, with intermittent fine sandstone and chert. Thin beds of fine sandstone, interpreted as distal turbidites, are present throughout a section cored at DSDP Site 269, and intercalated silty clay beds contain ice-rafted clasts. A silty sandstone from near the Miocene-Pliocene boundary (~5 Ma) contains detrital zircons with a mixed Precambrian age distribution. In order of decreasing abundance, these include Paleoproterozoic (1600-1750 Ma, with a peak at ~1610 Ma), Mesoproterozoic (900-1300 Ma), and Neoproterozoic (700-850 Ma) ages, as well as some of Ross Orogen age. Several grains have Mesoproterozoic ages of 1440-1460 Ma, unique to these samples from the Wilkes margin but observed in older sediments elsewhere. Two grains have ages >3.0 Ga, with the oldest of 3484 ± 4 Ma. Overall, the highly mixed age distribution in this sample reflects a heterogeneous source terrain or, more likely, a mixture of first-

and second-cycle detritus involving both local and distal sources. The low abundance of Ross Orogen detritus indicates that the continental rise was receiving mostly cratonic inputs at the time of late Neogene glaciation. It is also possible, however, that it contains contributions from along-shore currents that are not representative of local basement sources.

Holocene glaciomarine deposits

Offshore Holocene glaciogenic deposits along the Wilkes Land margin include glaciomarine diamicts containing basement rock clasts and fine-grained siliciclastic detritus. Rock clasts can be divided into 18 lithotypes comprising 81% metamorphic (mainly phyllite, meta-arenite, gneiss, granitic gneiss, granulite and charnockitic gneiss), 14% igneous (calc-alkaline granitoid and tholeiitic diabase with about a 2:1 ratio) and 5% sedimentary rocks (arenite and graywacke). From the clast population, the glacial provenance on the Wilkes Land margin is dominated by low-grade siliceous metasedimentary rocks, coupled with a heterogeneous mixture of igneous and high-grade meta-igneous rock types. Granitoid clasts have trace elements indicating crustal sources in a volcanic-arc setting; two have U-Pb zircon crystallization ages of ~510 and ~515 Ma, likely derived from the Ross Orogen. Five other igneous clasts have ages between ~500-520 Ma, with two others at ~585 and 1725 Ma. Six metamorphic clasts of ~500 Ma age contain discrete zircon age populations of 670-780, 900-1300, 1740-2300 and >2700 Ma that are probably detrital relics and reflect ages of primary source materials. A charnockite gneiss and granulite gneiss have metamorphic ages of ~1740 and 1720 Ma.

Sediment cores collected on the continental shelf and outer rise provide samples of glaciogenic sediment delivered from the interior of Wilkes Land. Detrital zircon populations from four Holocene glaciomarine sediments vary with depositional age, but show persistent terrigenous provenance ages of 540-590, 780, 1000-1260, 1460, 1610-1660, 1760, 2235-2450 and 3070-3485 Ma. These ages overlap significantly with inherited zircons in clasts of Ross-age granitoids. Of these, Grenville-age (1200-1260 Ma), Paleoproterozoic (~1665 and ~1760 Ma) and late Archean (2450-2570 Ma) ages suggest that pre-Ross basement underlying the Wilkes margin is dominated by Archean and Paleoproterozoic crust, as seen in coastal outcrop (Peucat et al., 1999).

Together, these data suggest that East Antarctic basement inland from the Wilkes Land margin is dominated by metamorphic rock units with distinctive Neoproterozoic, Paleoproterozoic and Archean ages, and that Ross-age granitoids either intruded or were derived by partial melting of this composite metamorphic basement. Integration of data from petrologically-distinctive individual clasts and large detrital zircon populations therefore provides a good first-order representation of the EAS terrains underlying the Wilkes Land ice sheet.

Summary

In summary, sediments transported from the Antarctic interior to the margin provide important composition and age information about East Antarctic shield geology. In both the central Transantarctic Mountains and the Wilkes Land cratonic margins, sedimentary and glacially-derived materials of various ages spanning the Proterozoic to Pleistocene can provide information about the East Antarctic shield interior. This type of information can refine our understanding of East Antarctic geology, helping to test proposed reconstructions of the Rodinia and Gondwana supercontinents, and to provide guidance for future remote sensing (mainly airborne geophysics) and drilling operations.

Acknowledgments. This work is supported by the U.S. National Science Foundation (awards provided through the Office of Polar Programs, Antarctic Geology and Geophysics Program). I thank Jim Collinson, Eugene Domack and Amy Leventer for early support in providing sample materials to get things started. Several students contributed to these ongoing studies, including Devon Brecke, Katie Brosch and Diane Curelli. I also thank collaborators Andy Barth, Peter Braddock, Mark Fanning, Kathy Licht, Paul Myrow and Ian Williams, who have contributed centrally to these projects. Last, I thank the following individuals and institutions for help in obtaining sample material: (1) Eugene Domack (Hamilton College) and Amy Leventer (Colgate University), co-investigators of the CHAOS cruise of the R/V *Nathaniel B Palmer* NBP01-01; (2) Matt Curran (Florida State University and Antarctic Research Facility); (3) Gar Esmay (Lamont-Doherty Earth Observatory and ODP core repository); and (4) Anne Grunow (Ohio State University and U.S. Polar Rock Repository).

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